

地质力学的方法与实践

第三篇

岩石力学与构造应力场分析

陈庆宣 王维襄 孙 叶 等 编著



地质出版社

地质矿产部“八五”重要基础研究项目

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· 北 京 ·

内 容 提 要

本书依照李四光教授的遗愿撰写而成,是他逝世(1971年)以后20多年来,地质力学和有关学科在岩石力学性质及构造应力场分析方面研究成果的总结归纳。本书叙述了岩石力学性质的实验观测与自然表象的基本问题,重点讨论了岩石的变形与流动,以及断裂与损伤;在介绍构造应力场基本概念的基础上,首先讨论了地质历史时期构造应力场的研究方法、典型构造型式、发展演化及其应用等;重点叙述了现今构造应力场研究中的地应力测量工作、研究方法、典型构造型式、短周期的发展变化和应用研究等;举例分析了中国区域现今三维构造应力场的基本特征,以及全球性分布规律,旨在把它与探讨地壳运动联系起来,并进一步从构造应力场的模拟实验研究(包括非均匀介质三维光弹模拟方法等)及理论分析,验证各种典型构造形式与全球构造应力场的分析结果。本书对从事构造地质、矿产地质、环境地质、灾害地质、地震地质、地热地质、深部地质、历史地质以及大地构造研究的科研人员与高等院校师生均有重要参考价值。

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序

与地质力学密切相关的第一篇文章“地球表面形象变迁之主因”发表于1926年。构造型式和构造体系的概念是在本世纪20年代末期提出的(Lee, 1929)。结合中国大陆及东亚地区的地质实际,根据地球表面实际见到的不同型式的构造体系来论断地壳运动的,是1939年出版的《中国地质学》(英文版)一书。地质力学作为一门学科是1941年秋冬之际,李四光教授应厦门大学校长萨本栋教授之邀为该校数学力学和物理系(当时由于抗战该校迁至福建长汀)的同学讲演时提出的。之后,李先生开始写《地质力学之基础与方法》,并于1945年完稿。该书稿曾由重庆大学地质系油印,当时,在重庆的中国地质学会同仁还举行过多次学术报告会。该书于1947年春由中华书局正式出版。

1949年10月1日中华人民共和国成立后,为了适应国家经济建设需要,开展了大量地质工作,包括矿产勘探、工程地质、水文地质以及国家建设中出现的其他各种地质问题。地质力学在李四光教授亲自领导和参与下投入到国家建设洪流之中,与其他地质科学一样取得了迅速的进展。60年代初,内部出版了《地质力学概论》。1970年,内部刊印了《天文、地质、古生物资料摘要(初稿)》一书。上述两本书均由李先生亲自执笔。书中不少的地质实际资料是由各方面的地质工作者提供的。

李四光教授在他早年和晚年的著作中均曾提出过:地质力学的主要目的是研究地壳构造和地壳运动的规律,探索地球运动的起源;研究各种矿产在地壳中的分布规律以及现代地壳运动的程式,借以指导矿产资源预测以及地壳稳定性评价,防治可能发生的各种自然灾害。

李四光教授在其遗著中曾提示我们:研究地球科学,要从地球看宇宙,要以事物的生因、发展和系统联系的观点,从事实现象追寻本质的要求,来研究地壳运动所产生的各种地质现象发生、发展的规律。

从李四光教授1926年发表第一篇文章起至1971年4月底他逝世这45年间,他为地质力学学科的建立及应用做了大量的实际工作,开辟了地壳运动研究的一条新途径,为发展地球科学作出了重要贡献。从李四光教授逝世到现在,许多地质工作者沿着他开拓的道路又进行了21年的工作。从1926年到现在这66年间,在国家经济建设和人类社会生活需要的各种自然资源的寻找以及与人类生存相关的各种自然灾害的斗争中,地质力学伴同其他地球科学做了大量的有益工作。《地质力学的方法与实践》丛书,就是这项工作的一种记录。今后,我们将把这项工作继续下去,为认识自然和改造自然作出新的贡献。

孙殿卿

1994年11月14日,北京

PREFACE

The first paper closely related to geomechanics entitled the "*Main Cause of the Changes of Superficial Features on the Earth*" was published in 1926. As for the conception about the tectonic patterns and tectonic systems, it was put forth at the end of the twentieth century (Lee, 1929). It was in the book entitled the "*Geology of China*" (in English version) published in 1939 that the crustal movement had been proved by the author with the tectonic systems of different types actually found on the surface of the Earth, and in combination of the practical geological situation in the mainland of China and East Asia. Geomechanics as a branch of sciences was established in the autumn and winter time of 1941 by Prof. Li Siguang (J. S. Lee) during his lecturing for the students from the Department of Mathematics, Mechanics and Physics of the Xiamen University (moved to Changding City, Fujian Province owing to the anti-Japanese War) at the invitation of the Dean of the University. Later on Prof. J. S. Lee began to prepare the book on "*The Basis of Geomechanics and Its Method*", which was completed and was mimeographed by the Department of the Geology of the Chongqing University, Sichuan Province in 1945, and at the same time it was then once used as lectures for the colleagues of the Geological Society of China at Chongqing City. The particular monograph was officially published by the China Publishing House in the spring of 1947.

Since the founding of the People's Republic of China on October 1, 1949, in order to meet the need of the economic construction of the country vast amounts of geological work have been conducted, including prospecting for mineral resources, engineering geology, hydrogeology and various geological problems that have been occurred during the economic construction of the country. So geomechanics has been thrown into the mighty torrent of the economic construction of the country under the direct guidance of Prof. J. S. Lee himself and his personally taking part in the work, and as other branches of geological sciences, geomechanics in this way has also gained a rapid development. At the beginning of the 60's of this century the monograph: "*An Introduction to Geomechanics*" was published as a restricted publication, and in 1970 the monograph: "*Astronomy, Geology and Palaeontology*" (first draft) was also published as a restricted publication. All the above-mentioned monographs were written by Prof. J. S. Lee himself personally, by using a big amount of practical geological data provided by vast numbers of geological workers from various fields.

In his works published in his early and late years, Prof. J. S. Lee had repeatedly remarked that the major objective of geomechanics lies in the study of the regularity of crustal

tectonics and crustal movement, in probing into the origin of the movement of the Earth, and in investigation on the regularity of distribution of various mineral resources in the earth crust, as well as on the mode of occurrence of the modern crustal movement, with the purpose of guiding the prognostication of mineral resources and making the evaluation of the stability of the earth crust, thus preventing from the possible occurrence of these and those natural hazards.

In his posthumous works, Prof. J. S. Lee used to mention to the audience that in the study of geological sciences one must view the cosmos from the Earth and investigate the regularity of occurrence and development of various geological phenomena produced by the crustal movement from the viewpoint of the origin, development and systematic relations, and in accordance with the requirement of study on any matter by probing into the essence of things judging from the phenomena of the fact.

During the forty five years of his life, starting the publication of his first paper in 1926, and being ended with his death at the end of April in 1971, Prof. J. S. Lee had completed large amounts of practical work for the establishment and application of geomechanics as a branch of sciences, and had opened up a new approach to the study of the crustal movement, thus making a great contribution to the development of geological sciences. From the time of his passing away till the present, many geological workers have conducted great amounts of work for twenty one years along the path Prof. J. S. Lee had opened up. In the 66 years from 1926 till now, in the prospecting for natural resources needed for the economic construction of the country and social daily necessities of human beings, as well as in the struggle against various natural hazards that are closely related to the existence of human beings, together with other branches of sciences geomechanics has done a lot of useful things. The "*Method and Practice of Geomechanics*" series represent itself records of this kinds of work. In the future we will certainly keep taking this kind of records in order to make a new contribution to recognition and remaking of nature.

Sun Dianqing

November 14, 1994, in Beijing

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引 言

地球科学界正热烈地通过各种不同的途径研究岩石圈和全球动力学。地质力学工作者也积极地按照自己多年来形成的途径,即将地质学、地球物理学、地球化学和力学等多种学科结合起来,通过对地壳地质构造和地壳运动的研究,以深化地球动力学和运动学的研究。

因为,地壳虽然是地球整体结构中极薄的一层,但她却记录和保存下了地球形成、发展、演化的踪迹;记录和保存下了地壳以外,诸如包围地球的大气层,围绕地球转动的月球,太阳系,以及其它各种星体对地壳发生的影响,宇宙微尘和陨星之类的坠落等(星)球外事件的遗迹;记录和保存下了地壳以下,在高温高压条件下,地球各圈层物质的物理与化学变化和运动,以及由重力、日月潮汐作用和地球自转而产生的运动,都不可避免地要集中反映到地壳中来。

由此看来,如果其它研究地球动力学途径是科学的、有成效的,那么,地质力学以地壳为对象,通过对地壳地质构造、物质的运动和分布规律、地壳运动的起源和演化等的研究,由表及里、由浅及深、由局部到地球整体,深入地研究地球各圈层的组织构造、相互作用,地球的起源、演化和运动等一系列地球动力学和运动学问题,是不无道理的。

为此,地质力学工作者经过了长期的奋斗,在她自己的努力和各相关学科、广大科学工作者的支持下,做了大量的工作,取得了很多、很有意义的成果。经常地、及时地综合分析研究、总结这些成果,不仅对发展地质力学具有重要意义,对于发展地球科学,促进地质力学更好地为社会发展和国民经济建设服务,也不会没有意义的。地质矿产部和中国地质科学院将《地质力学的方法与实践》列为“八五”重要基础研究项目,在孙殿卿院士指导下予以实施。

早在 60 年代初,地质力学的创始人李四光教授就计划组织人力,编著一套《地质力学的方法与实践》丛书,总结地质力学研究和实践成果。为此,他亲自草拟大纲,并将他自己主持撰写的《地质力学概论》专著做为该丛书的第一篇。其后,他还提出了对《地质力学概论》进行修改的意见。

这次的综合研究和总结工作,就是实现李四光教授的遗愿,修订第一篇,编著四篇六本书和一幅全球构造图,即:

第一篇 地质力学概论 李四光著,孙殿卿等修订

第二篇 构造体系各论《中国典型构造体系分论》 王治顺等编著

第三篇 岩石力学与构造应力场分析 陈庆宣、王维襄、孙叶等编著

第四篇 地壳运动问题 高庆华等编著

现今地壳运动问题 马宗晋、杜品仁编著

第五篇 地质力学在矿产资源勘查中的作用 刘迅等编著

地质力学在环境地质中的应用 邵云惠等编著

全球构造体系纲要图 苗培实等主编

《地质力学的方法与实践》既然是在广大地质力学工作者和有关学科科学工作者科学研

究与实践应用成果基础上,经过综合分析研究、总结完成的一套丛书,无疑也是大家劳动成果的结晶。因此,除《地质力学概论》一书外,其它各篇册我们都用了“编著”一词,表示这一套书中还包含了他人的成果,并在此予以致谢。如果有什么疏漏和引用上的误解,也请予以批评指正。

《地质力学的方法与实践》编辑委员会

INTRODUCTION

The geosciences circles have now been heartily investigating the lithosphere and global dynamics in different ways. Meanwhile, the geomechanic workers have also actively deepened their investigations on the dynamics and kinematics of the Earth in a way created by themselves in the passing years, namely by combining the geology, geophysics, geochemistry and mechanics with one another, and through the study of geological structures on the earth crust and crustal movement.

So although the earth crust tends to constitute only a thin layer in the whole texture of the Earth, yet it has recorded and preserved all the features formed in the course of origin, development and evolution of the Earth; the results of the influence from the atmosphere surrounding the Earth, the moon rotating around the Earth, solar system, and the other celestial bodies upon the earth crust; as well as the traces of the outer-space events, such as the fall of the cosmic dust and meteorites. Besides, in the earth crust there must have undoubtedly been recorded and preserved in a concentrated way all the expression, under high temperature and pressure, of physical and chemical changes and motion of matter in the litho-, hydro-, air-, and bio-spheres of the Earth.

In view of this, if the other approaches of the study of geodynamics are considered to be scientific and effective, then the geomechanics with the earth crust being as its target of research should also be valid and reasonable, since it keeps to the principle of going deep into the study of geodynamic and kinematic problems concerning the structure and texture of the litho-, hydro-, air-, and bio-spheres of the Earth, mutual actions of the later, as well as the origin, evolution and motion of the Earth in a way proceeding from the outside to the inside, from the simple to the profound, and from the part to the totality through the study of the geological structures of the earth crust, the motion and regularity of distribution of matter in the earth crust, and the origin and evolution of the crustal movement.

For this reason, the geomechanical workers have conducted a great volume of work and have gained lots of meaningful results through their protracted struggle, and with their own effort and under the support of the interrelated branches of sciences and vast numbers of scientists. The frequent and timely comprehensive analysis and summation of these achievements and results are of great importance not only to the development of geomechanics, but also to the development of the whole geological sciences themselves and to promoting geomechanics to provide a better service for social development and national economic construction. With the support from the Ministry of Geology and Mineral Resources and the Chinese Academy of Geological Sciences, the publication of *the Method*

and Practice of Geomechanics series has been placed in the "Eighth Five-Year Plan of the Development of Natural Sciences" as an important project of basic researches to be implemented under the guidance of Academician Sun Dianqing.

As early as at the beginning of the 60's of this century. Prof. J. S. Lee, the founder of geomechanics used to plan to organize labour power to compile a set of *the Method and practice of Geomechanics series*, aiming at the summation of the achievements and results of the research and practice of application of geomechanics. For this purpose, Prof. J. S. Lee personally took a hand in drafting an outline for the particular series, and decided to take the monograph of his *An Introduction to Geomechanics* as the first volume of this series. Later on, Prof. J. S. Lee made comments on the revision of the monograph *An Introduction to Geomechanics*.

The present comprehensive research and summation is exactly the implementation of the behests of Prof. J. S. Lee, modifying the first volume and compiling six books of four volumes and a sheet of Global Tectonic Map, namely:

Volume I, *An Introduction to Geomechanics*, by J. S. Lee, modified by Sun Dianqing and Others;

Volume II, *Separate Treatises on Tectonic Systems* (Individual papers on typical tectonic systems of China) by Wang Zhishun and Others;

Volume III, *Rock Mechanics and Analysis Tectonics Stress*, by Chen Qingxuan, Sun Ye, Wang Weixiang and Others;

Volume IV, *The Problems on Crustal Movement*, by Gao Qinghua and Others;

The Problems on Recent Crustal Movement, by Ma Zongjin and Du Pinren;

Volume V, *Application of Geomechanics in Prospecting for Mineral Resources*, by Liu Xun and Others;

Application of Geomechanics in Environmental Geology, by Shao Yunhui and Others;

An Outline Map of Global Tectonic Systems, by Miao Peishi and Others;

As the method and Practice of Geomechanics series has been compiled on the basis of comprehensive analysis and summation of the results of research and practice conducted by vast numbers of geomechanical workers and scientists engaged in related branches of sciences, so it should undoubtedly be regarded as a crystallization of common effort of all the people concerned. Except for the monograph *An Introduction to Geomechanics*, for all other volumes of the series we use the term "Compilation", to mean that in the particular series results of research by other people are included, which the authors beg to acknowledge hereby. So and comments on possible oversights and omissions and mistakes in quotations are welcomed.

Editorial Board of *The Method and Practice of Geomechanics*

前 言

《岩石力学与构造应力场分析》是地质矿产部“八五”重要基础研究项目——“地质力学的方法与实践”专题研究之一。它是在研究、总结岩石力学和构造应力场实验和理论研究成果的基础上完成的一部专著。

李四光教授早在 20 年代就注意到岩石在长期持续应力作用下的形变问题,并着手研究岩石形变与应力作用之间的关系,目的在于从某一场构造运动所产生的地壳各个区域的各项形变及其特定组合在空间上展布的规律性,去追索它们之间在该构造运动中相对运动的方式和方向。从那时以来,这一方面的工作已经取得了丰硕的成果。

岩石对应力作用的反应,取决于诸多复杂的因素,主要可分为两大方面。其一是岩石发生变形时所处的物理环境,包括温度、围压、存在于岩石和地壳中的流体、所受应力的大小及其作用的持续时间;另一方面是岩石的物质组成和力学性质。具有不同力学性质的岩石在完全相同的物理条件下可表现为不同性质的变形,如坚硬的厚层英石砂岩可表现为脆性断裂,而相邻的软弱薄层灰岩则表现为韧性流动。这种现象在野外屡见不鲜。另外,岩石的成层厚度(如块状、厚层、薄层等等),不同岩性、不同厚度岩层的相互组合关系和它们相互之间的粘度比等等都对岩层的受力反应有很大影响。探索研究岩石在一定物理条件下的短期和长期变形行为,对深化认识地质构造现象,对在有关学科中以及在岩土工程建设中加以实际应用,都有重要意义。

人们经常利用某一期构造运动在岩石中保留下来的永久形变痕迹,包括宏观的和微观的,来恢复一个地区那一时期的构造应力场,同时利用地应力测量方法测定同一地区的现今地应力状态,借以研究这个地区某个地质时期以来,地应力场的演化历史,并预测将来可能的发展趋势,为区域构造稳定性评价提供必要的定量化依据。本书举出了一些实例,同时还总结了地应力随深度的变化规律以及区域性和全球性分布规律。

在构造应力场理论分析与模拟实验方面,本书介绍了数学模拟和物理模拟几种常用的方法;对纬向、经向和扭动三种典型构造型式进行了理论分析和单层二维物理模拟的结果以及全球应力场的初步研究成果;发展建立了多层非均匀介质三维光弹模拟方法。

鉴于岩石力学(性质)与构造应力场不可分割的密切联系,本书将两者结合起来,按照李四光教授遗愿,命题为《岩石力学与构造应力场分析》,主要围绕地质力学研究、地壳构造、地壳运动遇到的有关岩石形变的力学问题和应力场问题进行撰写。

这本书是集体劳动成果。陈庆宣院士进行全书的设计、指导、定稿,编写前言和英文摘要,王襄教授编写第一、二、三章,孙叶研究员协助统稿,同时编写第四、五章和第六章的第二至七节,王连捷研究员编写第六章的第一节,黄庆华研究员编写第七章,苗培实研究员多次审阅全稿和参加讨论修改等。李淑芬工程师进行插图的设计和清绘,杨贵生助理工程师进行电脑文字处理、打印以及数据计算工作,谭成轩博士帮助本书作了许多工作,……在此一并致谢。

陈庆宣、苗培实

1996 年 5 月 16 日

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第一章 岩石力学性质的实验观察 与 自然 表 象

岩石的力学性质是地质力学研究的一个基本问题。地质力学对岩石力学性质的研究、了解和资料的取得,主要来自三个方面:①野外调查;②室内实验观察,包括现场实地观测;③理论分析。

室内实验观察是目前一般岩石力学性质常规研究的主要方法,为了解岩石在地壳内受应力作用的反应,在实验室内模拟地壳内的物理环境,观察岩石受力变形过程和相关数据的测定。

地壳内部的物理环境由温度、压力、孔隙流体压力等多种因素构成。在实验室内同时模拟多因素环境条件常常十分困难,特别是在高温、高压下再考虑其他影响因素,实验设备、技术要求较高,投资较大。为系统了解岩石的力学性质,变形、流动和断裂的规律,开始是在各种单因素条件下进行实验观测,继而在两种、三种、多种因素条件下进行实验研究。

野外调查是通过对地质构造表象、岩石成分、地质年代、构造环境等进行观察分析,或者对地壳长期缓慢和瞬间剧变的位移变形进行观测,研究地壳岩石的力学性质。例如,从岩层褶皱、变形化石和变形砾石,看到岩石的非弹性;从冰后大陆持续上隆看出大陆壳的弹粘性;从地震波的传播和衰减,看出地壳乃至地幔的弹塑性;从基岩断裂穿刺连续盖层,显示出基底和盖层两类岩石在力学性质上的巨大差别(图 1-1),前者表现为脆性断裂,后者表现为韧性变形,等等。野外调查是研究地壳岩石力学性质最直接也是最先一步的工作。只有先观察到构造表象,对相关各种因素有了充分了解之后,才能运用力学原理和室内实验方法进行综合研究,以期对问题取得实质性和规律性的认识。现场实地观测,在工程地质中应用较多,但只限于浅层和局部。通过物探资料可以推算地壳岩石的一些物性参数,这是取得地壳内部岩石力学性质参数的一种常用方法。但这种方法要先对地壳岩石力学性质予以选定或建立合适的力学模型,然后再进行物性参数推算。

岩石力学性质理论分析,在岩石力学性质研究中的重要意义。研究中除了测定一些物性参数外,更重要的是,寻找岩石在应力作用下,力学性质的表现和变化规律,即本构关系。因为参与反映某一变形过程的本构因素多含有两个以上的多个成分,诸如应力张量、应变张量、应变速率张量、时间等。而各张量在三维空间中都有九个分量,如果通过实验的方法,寻找反映各种力学性质的表现和本构因素间的变化规律,各种本构因素分量具有无穷组合,对各种组合探讨它们所满足的关系,工作量太大,将无法完成。对于这种情况,要通

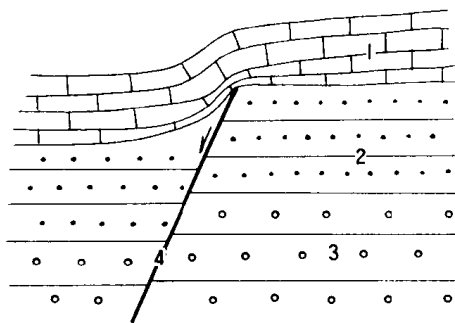


图 1-1 基岩断裂穿刺连续盖层素描图

Fig. 1-1 Sketch showing continuous cap rock penetrated by basement fracture

1—薄层灰岩;2—厚层砂岩;3—厚层砾岩;4—断层